Original Paper

Phonetica 2008;■:1–17
DOI: 10.1159/00010■■■■

Received: May 2, 2007
Accepted: February 24, 2008

Prosodic Strengthening in Transboundary V-to-V Lingual Movement in American English

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Abstract

This study investigates how prosodic strengthening is kinematically manifested in V-to-V lingual movement in English CV#CV context (where # is a prosodic boundary). Results showed that both boundary and accent gave rise to a kind of prosodic strengthening (showing spatial and temporal expansion), but exact kinematic patterns of prosodic strengthening were different as a function of the type of gesture (tongue lowering versus raising) associated with different vowels (/i/-to-/a/ vs. /a/-to-/i/) and the source of prosodic strengthening (boundary versus accentuation). This implies that speakers must know about prosodic structure and differentiate the two sources of prosodic strengthening in a systematic fine-grained fashion. From a theoretical point of view regarding a mass-spring gestural model, results suggested that kinematic patterns of prosodic strengthening could not be fully accounted for by any particular dynamical parameter, presenting a complex nature of prosodic strengthening. The results also implied that the theory of the π-gesture (the prosodic boundary gesture) under the rubric of the mass-spring gestural model needs to be refined in terms of how the theory defines the exact scope of the π-gesture's influence in the temporal dimension and how it differentiates boundary-induced articulation from an accent-induced one.

1. Introduction

A spoken utterance's linguistic message is manifested not only in its lexical and syntactic structures, but it is also known to be reflected in its prosodic structure, according to which grouping of words into larger prosodic constituents and relative prominence among the words are determined [e.g., Beckman, 1996; Shattuck-Hufnagel and Turk, 1996]. Prosodic structure is taken to modulate speech production [e.g., Keating and Shattuck-Hufnagel, 2002], which is primarily evident in fine-grained 'prosodic strengthening' patterns in prosodic landmark locations such as prosodic domain edges and syllables with prominence. Here the term 'prosodic strengthening' is defined as spatial and temporal expansion that arises with prosodic landmark locations [e.g., Cho, 2005; Cho and McQueen, 2005]. Phonetic hallmarks of prosodic structure have often

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been documented to be most clearly evident in the temporal dimension, showing lengthening in prosodic landmark locations, such as in accented syllables [e.g., de Jong 1991; Beckman et al., 1992; Fowler, 1995; Erickson, 2002; Mooshammer and Fuchs, 2002; Cho, 2006] and at prosodic junctures [e.g., for preboundary (domain-final) lengthening: Edwards et al., 1991; Gussenhoven and Rietveld, 1992; Wightman et al., 1992; Berkovits, 1993; Byrd, 2000; Cambier-Langeveld, 2000; Byrd et al., 2006; Cho, 2006; for postboundary (domain-initial) lengthening: Fougeron and Keating, 1997; Byrd and Saltzman, 1998; Byrd et al., 2000; Cho and Keating, 2001; Keating et al., 2003; Cho and McQueen, 2005; Byrd et al., 2006; Cole et al., 2007; Krivokapić, 2007, inter alia].

The boundary-adjacent lengthening effects at both edges of prosodic domains have been generally demarcated into pre- and postboundary phenomena, in such a way that the degree of final lengthening is closely correlated with the size of prosodic domains such as the Prosodic Word, the Intermediate Phrase and the Intonational Phrase [Beckman and Pierrehumbert, 1986; see Shattuck-Hufnagel and Turk, 1996, for a review of various prosodic constituents in English]. There is yet another type of boundary-adjacent temporal variation that encompasses both the pre- and postboundary components. Byrd [2000], for example, examined temporal characteristics of 'transboundary' articulatory movement that spans a prosodic boundary – i.e., temporally expanded V-to-V lingual movement which passes over a prosodic boundary from the preboundary to the postboundary vowel (as in *Momma#Mimi*, where # is some prosodic boundary). The results of this study suggested that the boundary-adjacent lengthening may be most effectively manifested in the transboundary articulatory movements, again in close relationship with the size of intervening prosodic boundary [for V-to-C transboundary movement effects, see Byrd et al., 2006, and Cho, 2006, for English data, and Tabain, 2003a, b and Tabain and Perrier, 2005, for French data].

One of the goals of the present is to investigate the temporal characteristics of these transboundary V-to-V vocalic movements in English *b*V1#*b*V2 sequences. Byrd [2000] has initially investigated boundary-induced variation in V-to-V vocalic movements, but the present study extends Byrd's study by considering accent as an additional factor in order to examine how boundary and accent interact with each other.

Some researchers have in fact previously proposed that accent-induced lengthening and domain-final lengthening differ kinematically, each governed by different dynamical mechanisms – i.e., the intergestural timing account and the stiffness account, respectively [e.g., Edwards et al., 1991; cf. Harrington et al., 1995]. The intergestural timing account explains the accent-induced articulatory lengthening as a result of the delayed timing of the following gesture relative to the target gesture, hence a full temporal expansion of the (nontruncated) target gesture [cf. Byrd and Saltzman, 2003]. In such a case, an increase in both duration and displacement is expected with velocity remaining unchanged, which was indeed what Edwards et al. [1991] observed with the jaw opening and closing movements. On the other hand, the stiffness account assumes that boundary-induced final lengthening is due to the gestural stiffness – i.e., the less stiff the gesture, the slower the movement. The stiffness account predicts no change in displacement but does predict increased duration (due to decreased velocity). The jaw movement in domain-final position indeed showed such a pattern which led them to conclude that the stiffness underlies domain-final articulation. (See Saltzman and Munhall [1989]; Browman and Goldstein [1990, 1992], and Hawkins [1992] for reviews of dynamical parameters.)

A more recent lip kinematic study by Cho [2006], however, demonstrated that as far as the lip aperture in English is concerned, the boundary- versus accent-induced articulatory lengthening cannot be characterized with clearly differentiated dynamical accounts [see Byrd, 2006, for discussion]. For example, accented lip opening/closing gestures were found to be associated with higher peak velocity which is not expected by the intergestural timing account; boundary-adjacent lip opening/closing gestures often showed an increased displacement, which is not expected by the stiffness account. These results thus illuminated a complex nature of dynamical aspects involving prosodically conditioned kinematic patterns. Furthermore, the aforementioned previous studies have examined boundary- versus accent-induced lengthening effects only on C-to-V or V-to-C articulations for the jaw and the lips. It is therefore still unclear whether the same kinematic characteristics underlie articulatory gestures when a different articulator (e.g., the tongue) and a different kind of gesture (e.g., V-to-V articulation) are involved. More specifically, how does the accent-induced articulatory lengthening in C1V1#C2V2 differ from the boundary-adjacent lengthening, when the transboundary V-to-V lingual articulation is involved? And how do boundary and accent factors interact with each other? The present study explores these questions.

Another goal of the present study is to examine the degree of articulatory magnitude and its relationship with temporal variation as a function of boundary and accent, reflected in variation in V-to-V displacement. Examining prosodically induced variation in articulatory displacement is important because it not only helps us understand how boundary-versus-accent information is phonetically manifested in a spatial dimension, but it also allows us to understand dynamical mechanisms underlying prosodically driven articulatory variation, especially in terms of how any observed temporal variation in transboundary V-to-V lengthening is related to spatial variation.

Byrd has attempted to account for the boundary-adjacent articulatory lengthening in the framework of a mass-spring gestural model [see also Byrd and Saltzman, 2003; Byrd, 2006; Byrd et al., 2006; Krivokapić, 2007]. Departing from the gestural stiffness account [e.g., Edwards et al., 1991; Beckman et al., 1992], Byrd and Saltzman [2003] hypothesized that such boundary-induced temporal variation is governed by a so-called 'π-gesture' (the prosodic boundary gesture), which is an abstract and non-tract variable gesture, whose domain of influence is local to the edges of prosodic domains [see also Byrd, 2006]. They showed that the articulations that are immediately next to the prosodic boundary are influenced most by the π-gesture, and thus engender the strongest lengthening effect (possibly with some degree of strengthening in the spatial dimension). This was further supported by a computational simulation with a clock-slowing implementation. Byrd and her colleagues [e.g., Byrd, 2000; Byrd and Saltzman, 2003; Byrd et al., 2006; Krivokapić, 2007], however, have examined boundary-adjacent lengthening without considering its interaction with accent-induced lengthening and the complexity that might arise with possible boundary- and accent-induced spatial expansion. This leads to a question as to how the temporal variation and possible augmented articulatory magnitude stemming from the two different prosodic sources is treated in dynamical terms in their model.

The present study therefore addresses this issue along with investigation of boundary-versus accent-induced kinematic variation. (But see Saltzman et al. [2007] for a possible use of π-gesture in accounting for a lexical stress effect on articulatory timing.) As discussed earlier, if any observed articulatory lengthening under a certain prosodic condition were accompanied by an increase in articulatory magnitude but it arose with no change of movement peak velocity, the lengthening effect can be interpreted as attributable to the intergestural timing. It would then support the view that variation in intergestural timing is the major source of the lengthening whether it comes from domain-edges or accent-induced prominence. On the other hand, if a lengthening effect were found with no variation in the spatial dimension in a certain prosodic condition, clock-slowing assumed in the π-gesture model would be thought to be responsible for it.

Finally, the present study investigates whether the kinematic characteristics vary as a function of vowel type and directionality of movements. Perkell [1990] showed a vowel-related difference in direction of articulatory displacement, such that, for example, /i/ and /a/ are produced with different displacement variation. (See Cho [2005] on similar vowel-related differences in the static tongue extrema and their corresponding F1 and F2.) These results then lead to questions: are the prosodically conditioned strengthening effects kinematically the same even when vowel targets are different (/i/ vs. /a/) and when different sources of prosodic strengthening (accent versus boundary) are involved? If not, how do they differ? That is, the present study asks whether and how prosodic strengthening as in the /a/-to-/i/ gesture differs kinematically from that in the /i/-to-/a/ gesture.

2. Method

In order to examine effects of boundary and accent factors on kinematics of V-to-V lingual gestures, tongue movement data in American English were collected as part of a larger study along with movement data of other articulators using Electromagnetic Midsagittal Articulography (EMA, Carstens Articulograph AG 100).

2.1. Speech Material and Speakers

An experimental corpus of the articulatory data was built in the following ways. Each item in the corpus included two test syllables (pre- and postboundary) as in a *b*V1#*b*V2 sequence (where # = some prosodic boundary) across two words, where the first and the second vowels (V1, V2) were either /i/ or /a/, yielding four pairs: /i#bi/, /a#ba/, /i#ba/, and /a#bi/. Prosodic boundaries were expected to vary from the Intonational Phrase (IP) boundary, to the Intermediate Phrase (ip) boundary, to the Word (Wd) boundary, as they are three possible across-the-word prosodic boundaries in the framework of Tones and Break Indices (ToBI) [Silverman et al., 1992; Beckman and Elam, 1997]. In the ToBI transcription system, the IP boundary is detected when the final element (usually final one or two syllables) of the phrase is associated with a substantial tonal movement (either falling or rising or combination of the two, known as boundary tones marked by % as in L% or H%), which is usually accompanied by substantial lengthening (transcribed with break index 4). The ip boundary is similar to the Phonological Phrase [Selkirk, 1984] and is generally marked by some tonal movement (either falling or rising marked by L- or H-) after the last prominent syllable (i.e., nuclear pitch-accented syllable) to the end of phrase, but without substantial falling or rising as in the IP-final position at the end. The end of ip is usually accompanied by some degree of lengthening but not as extensive as at the end of IP boundary (transcribed with break index 3). The Wd boundary is defined as having neither noticeable tonal movement nor substantial lengthening as the end (transcribed with break index 1). (See Shattuck-Hufnagel and Turk, 1996, for discussion of different types of prosodic boundary.) Accentuation was manipulated in both the preboundary and postboundary syllables, resulting in four accentual combinations: ACC#ACC, ACC#UNACC, UNACC#ACC, and UNACC#UNACC.

For the purpose of the present study (examining the tongue raising/lowering movement), a subset of the data were examined including only /a#bi/ and /i#ba/ tokens in two accentual conditions (UNACC#ACC, UNACC#UNACC). Because the present study focused on how the accent factors on the target vowels (V2) would influence the kinematic patterns of the V1-to-V2 vocalic movement,

Table 1. The corpus containing /ba#bi/ and /bi#ba/ sequences with different prosodic boundaries (IP, ip, Wd) and postboundary accentual patterns

# = Word boundary	
(a) Accented	
Prompt	Did you say 'Little Bah **peeped** at him last night'?
Target (/a/-to-/i/)	No, 'Little Bah # **beeped** at him.' (/a/-to-/i/)
Rendition	(L+)H* L-L%
Prompt	Did you say 'Donna B. **popped** the girl last night'?
Target (/i/-to-/a/)	No, 'Donna B. # **bopped** the girl.'
Rendition	(L+)H* L-L%
(b) Unaccented	
Prompt	Did you say '**Big** Bah beeped at him last night'?
Target (/a/-to-/i/)	No, '**Little** Bah # beeped at him.'
Rendition	(L+)H* L-L%
Prompt	Did you just say '**Anna** B. bopped the girl last night'?
Target (/i/-to-/a/)	No, '**Donna** B. # bopped the girl.'
Rendition	(L+)H* L-L%
# = Intermediate or Intonational Phrase boundaries (ip or IP)	
(c) Accented	
Prompt	Did you say '**Big** Bah **peeped** at him last night'?
Target (/a/-to-/i/)	No, '**Little** Bah # **beeped** at him.'
Rendition 1	(L+)H* L- (L+)H* L-L%
Rendition 2	(L+)H* L-L% (L+)H* L-L%
Prompt	Did you say '**Anna** B. **popped** the girl last night'?
Target (/i/-to-/a/)	No, '**Donna** B. # **bopped** the girl.'
Rendition 1	(L+)H* L- (L+)H* L-L%
Rendition 2	(L+)H* L-L% (L+)H* L-L%
(d) Unaccented	
Prompt	Did you say '**Big** Bah beeped at **Ann** last night'?
Target (/a/-to-/i/)	No, '**Little** Bah # beeped at **Al**.'
Rendition 1	(L+)H* L- (L+)H* L-L%
Rendition 2	(L+)H* L-L% (L+)H* L-L%
Prompt	Did you say '**Anna** B. bopped **the boy** last night'?
Target (/i/-to-/a/)	No, '**Donna** B. # bopped **the girl**.'
Rendition 1	(L+)H* L- (L+)H* L-L%
Rendition 2	(L+)H* L-L% (L+)H* L-L%

tokens whose accentuation varied only in the target vowels were included for analysis while the preceding vowel was controlled to be unaccented. The experimental materials therefore contained a total of 12 different sequences (3 prosodic boundaries × 2 accentual patterns in the postboundary syllable × 2 vowel types: /biba/ vs. /babi/). The target carrying sentences are given in table 1.

Six American English speakers (4 phonetics graduate students and 2 phonetics postdoctoral fellows at UCLA) participated in the experiment. They were all trained in the production of English sentences in the ToBI framework, prior to the experiment. To induce production of the intended renditions as effectively as possible, each speaker practiced the sentences with different prosodic patterns in an approximately 2-hour-long practice session before the actual recording date. (See section 2.4 for methodological limitations of this type of data generation.)

2.2. Procedures

V-to-V sequences were obtained from sentences in a mini discourse situation which was designed to induce the desired variety of accent-placement patterns and prosodic groupings. In each target sentence, the words highlighted in bold received pitch accent as can be seen in table 1. The speaker read the prompt silently to cue the intended accent and boundary patterns, which were provided using partial ToBI transcriptions in the script. Speakers read each sentence twice in succession in a list and repeated the entire list again for a total of four repetitions per sentence. This yielded a total of 288 sentence tokens to be analyzed for this study (12 sentence types × 6 speakers × 4 repetitions).

An EMA system (Carstens Articulograph AG 100) was used to track articulatory movements of the articulators [see Schoenle, 1988; Schoenle et al., 1989; Tuller et al., 1990; Hoole, 1996 for more technical information on the Carstens system, and Perkell et al., 1992, for another articulography system (EMMA)]. In the data collection session, seven transducer coils were used. To correct for head movement inside the helmet, two reference transducers were placed on the nose and upper gumline (maxillary incisor). The remaining five transducers were placed on articulators: two on the upper and lower lips at the vermilion borders, one on the lower gumline of the mandibular incisor for monitoring the jaw movement, and three on the tongue (the tongue tip, midsection and dorsum). The exact location of coil placement on the tongue varied from speaker to speaker, depending on the size of the tongue: the tongue dorsum coil was placed on the rearmost point when the tongue was pulled out, which was about 5–5.5 cm from the tongue tip, and two other coils were mounted on the tip (about 0.5 cm from the apex) and on the midsection between the tongue tip and dorsum coils, respectively. Following Byrd [2000], kinematic data obtained from the tongue dorsum transducer coil was analyzed for the purpose of the present study, as it captures the vocalic movement most effectively.

The articulatory space with the obtained data was rotated so that the x axis was coincident with the bite (i.e., occlusal) plane and the y axis was perpendicular to that at the junction of the occlusal plane and the central maxillary incisor; and this was consistent across speakers [see Tabain, 2003b, and Byrd et al., 2006, for similar data processing, and Westbury, 1994, for a further discussion about the usefulness of the occlusal plane]. The EMA data were sampled at 500 Hz with subsequent low-pass filtering with a filter cutoff of 50 Hz, using Tailor (Carsten's data processing program; see http://www.linguistics.ucla.edu/faciliti/facilities/ physiology/ema.html).

The boundary types, and the presence or absence of nuclear pitch accent in the *b*V1#*b*V2 portion of the audio recording, were transcribed by 2 trained English ToBI transcribers (one the author), with the aid of an acoustic display. In general, pitch accents received either H* or L + H*, and three prosodic boundaries (IP, ip, Wd) were identified. The phrase tone was always L^-, and the boundary tone was either L% or H%. The 2 transcribers reached 100% agreement on locations of pitch accent in every token of the entire dataset. They differed only in a choice between the IP boundary and the ip boundary. Only tokens whose transcriptions were agreed on by the 2 transcribers were used for analysis. In the subset of the experimental corpus that was analyzed for this study, out of 192 sentences (2 vowel types × 2 accent types × 2 prosodic boundaries IP, ip × 4 repetitions × 6 speakers) that were intended to elicit a phrase boundary IP or ip, 182 sentences (94.8%) reached agreement. (Note that each speaker contributed 15–17 IP sentences and 14–17 ip sentences, showing a balanced distribution across boundary types.)

2.3. Measurements

The tongue movement data for /a/-to-/i/ and /i/-to-/a/ were obtained from the tongue dorsum transducer signals in the vertical (y) dimension. The onset and target timepoints of vocalic movements were determined by a velocity noise window around the zero crossings in the velocity signal. Recall that Byrd [2000] examined boundary effects on V-to-V articulation only in the vertical (y) dimension and discussed their dynamical implications bearing on the π-gesture model. To be compatible with Byrd's [2000] data, the present study will consider kinematic variation only in the y dimension. A velocity noise window was defined separately for each speaker as 10% of the highest peak velocities of each vertical and horizontal tongue movement across the entire dataset [Byrd, 2000]. Thus, the onset was defined to be at the timepoint when the coil started leaving its minimum position after the zero-crossing in the velocity signal which corresponded to 10% of the highest peak velocity. Likewise the target was defined to be when the coil reached its maximum, which corresponded to 10% of the highest peak velocity before the zero-crossing.

Various dependent variables were calculated based on timepoints of movement onset, target, and peak velocity. The measured variables that were examined are schematized in figure 1. As can be seen

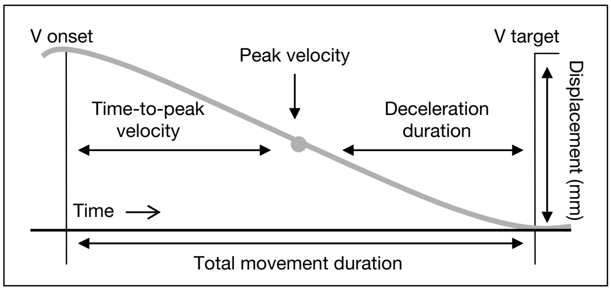

Fig. 1. Schema of the /i/-to-/a/ tongue lowering movement in the y dimension with an indication of the measured kinematic variables.

in the figure, five different measures were made. The measured variables include: (a) *displacement (mm)*: the amount of spatial difference between the onset and the target; (b) *total movement duration (mm)*: the interval from the onset to the target; (c) *time-to-peak velocity (acceleration duration, ms)*: the interval from the onset to the timepoint of peak velocity, which is sometimes referred to as acceleration duration; (d) *deceleration duration (ms)*: the interval from the timepoint of peak velocity to V target, and (e) *peak velocity (mm/s)*: the actual peak velocity value.

Among these measured variables are two durational components (measures c and d) of the total movement duration that requires further explanation. As noted by Byrd [2000], in examining boundary-induced durational variation, the *transboundary tongue* movement data do not tell us whether the variation in the total movement duration is caused by preboundary lengthening or by postboundary lengthening. This is because the transboundary gestures start before the prosodic boundary and end after it. This complex interval can be teased apart by breaking down the total movement duration into two durational components: the interval time-to-peak velocity (acceleration duration) and the deceleration duration. The lengthened time-to-peak velocity (the first component) may be interpreted to be more attributable to a preboundary effect and the lengthening of the second component (deceleration duration) to a postboundary effect.

The influence of the prosodic factors on these various measures was statistically evaluated by a series of repeated measures Analyses of Variance (RM ANOVAs), using SPSS 12.0 for Windows. There were three within-subject factors: Boundary (IP, ip, Wd), Accent (accented, unaccented), and V2 Type (/a/, /i/). Three-way RM ANOVAs were conducted with each speaker contributing one averaged score per condition, which has an effect of avoiding the type I (alpha) error [Max and Onghena, 1999]. Furthermore, in order to meet the sphericity assumption (when there were more than two levels for a given factor, in this case, Boundary), Huynh-Feldt-corrected degrees of freedom were used in generation F ratio and p values [Huynh and Feldt, 1970]. Degrees of freedom and error terms were therefore often reduced to fractional values [e.g., $F(2, 10) \rightarrow F(1.9, 9.2)$]. Due to such a conservative nature of the statistical analyses, significance would be produced only if any observed patterns are consistently found among speakers. When there was an interaction between factors, post-hoc tests (Bonferroni/Dunn) were employed in order to examine significance of differences between levels for each condition of the interacting factor. For example, when Accent interacted with V2 Type, the significance of difference between the accented and the unaccented level was tested for /a/ and /i/ separately.

2.4. Methodological Limitations

Before presenting the results, it is worth mentioning methodological limitations of the present study. The first concern has to do with types of focus. Accentuations may be expressed with various focus meanings such as ‘presentational’ focus (emphasizing part of the sentence that corresponds to the answer to a question), ‘contrastive’ focus (often referred to as ‘corrective’ focus), ‘reactivating’ focus (often obtained with topicalization) [see Gussenhoven, 2007 for a review]. Accent manipulation in the present study is done by inducing one type of focus – i.e., contrastive (corrective) focus [Chafe, 1974]. In addition, the way that the contrastive focus was obtained was by means of correcting the initial consonant, not the whole word (e.g., *peep* vs. *beep*) as seen in table 1. It should therefore be noted that although accentuation carried a nuclear pitch accent, its effect on articulation may differ from those obtained with different types of accentuation. Another concern is that production data were acquired from sophisticated speakers who were trained to control prosodic conditions as needed in the present study. Such a laboratory-controlled data elicitation procedure is likely to reduce implications of the present study for natural speech production. Any conclusions made in this study should therefore be taken with caution as they are valid only for this type of data generation with a particular type of accent.

3. Results

In the following subsections, the main effects of the Boundary and Accent factors on the five kinematic measures will be reported in connection with their interactions with V2 Type. At this point, however, it is worth mentioning one of the most striking results – i.e., none of the five kinematic measures showed either a two-way Boundary × Accent interaction or a three-way Boundary × Accent × V2 Type interaction. In most cases, therefore, any observed effects of Boundary and Accent can be considered to be independent from each other. The results are summarized in tables 2, 3 and figure 2. Note also that in tables 2, 3, when there is an interaction between Boundary and V2 Type (in table 2) and between Accent and V2 Type (in table 3), results of post-hoc tests are reported in order to see where the interaction has stemmed from.

3.1. Effects of Boundary on the Tongue Kinematics

One of the most interesting patterns that have emerged from the results regarding effects of Boundary is that all five kinematic measures showed a significant main effect with no Boundary × Accent interaction in all cases except for Time-to-peak velocity, as summarized in table 2. This suggests that prosodic boundaries are marked by all kinematic measures, independently from Accent effects in most cases.

Displacement. There was a significant main effect of Boundary on Displacement [$F(2, 10) = 7.24$, $p < 0.05$], and no Boundary × V2 Type interaction [$F(2, 10) = 2.13$, $p > 0.1$]. The main effect of Boundary arose from the pattern of IP > Wd for both /i/-to-/a/ and /a/-to-/i/, which suggests that V-to-V vocalic articulation is expanded at a larger prosodic boundary in the vertical (y) dimension, as shown in figure 2a.

Peak Velocity. The Peak Velocity measure showed significant main effects of Boundary [$F(2, 10) = 10.55$, $p < 0.05$], such that the tongue movement was slower at a larger prosodic boundary, showing a pattern of either IP < (ip = Wd) (fig. 2b). This effect was consistent across the vowel type as there was no Boundary × V2 Type interaction [$F(2, 10) = 1.98$, $p > 0.1$].

Total Movement Duration. A significant main effect of Boundary on Total Movement Duration was found [$F(1.9, 9.2) = 31.92$, $p < 0.05$], showing a pattern of IP > ip > Wd or IP > (ip = Wd) – i.e., a longer total movement duration was found across a larger prosodic boundary (fig. 2c). There was no Boundary × V2 Type interaction [$F(1.2, 5.8) = 2.69$, $p > 0.1$], showing that the boundary-induced lengthening effect was consistent across vowel type.

Time-to-Peak Velocity (Acceleration Duration) and Deceleration Duration. Both the acceleration and the deceleration duration measures showed a main effect of Boundary [$F(1.6, 8.0) = 13.86$, $p < 0.05$ for Time-to-peak velocity; $F(1.1, 5.7) = 6.75$, $p < 0.05$ for Deceleration Duration]. As shown in figure 2d, there was a predominant pattern of IP > (ip = Wd), with one three-way distinct pattern of IP > ip > Wd found for Acceleration Duration with /i/ target.

Table 2. Summary of Boundary effects on V1-to-V2 vocalic kinematics in the vertical (y) dimension

Kinematic measures	/i/-to-/a/ (downward)	/a/-to-/i/ (upward)
Displacement	main effect of Boundary: F(2, 10) = 7.24* Boundary × V2 Type interaction: F(2, 10) = 2.13$^{n.s.}$ post-hoc: IP > Wd	post-hoc: IP > Wd
Peak Velocity	main effect of Boundary: F(2, 10) = 10.55* Boundary × V2 Type interaction: F(2, 10) = 1.98$^{n.s.}$ post-hoc: IP < (ip = Wd)	post-hoc: IP < (ip = Wd)
Total Movement Duration	main effect of Boundary: F(1.9, 9.2) = 31.92* Boundary × V2 Type interaction: F(1.2, 5.8) = 2.69$^{n.s.}$ post-hoc: IP > (ip = Wd)	post-hoc: IP > (ip = Wd)
Time-to-peak velocity (Acceleration Duration)	main effect of Boundary: F(1.6, 8.0) = 13.86* Boundary × V2 Type interaction: F(1.4, 6.8) = 9.56* post-hoc: IP > (ip = Wd)	post-hoc: IP > ip > Wd
Deceleration Duration	main effect of Boundary: F(1.1, 5.7) = 6.75* Boundary × V2 Type interaction: F(1.1, 5.7) < 1$^{n.s.}$ post-hoc: IP > (ip = Wd)	post-hoc: IP > (ip = Wd)

Three-way RM ANOVAs showed no interactions between Accent and Boundary, indicating that Boundary effects are independent of Accent effects, but they showed Accent × V2 Type interactions in some cases. Therefore the results are reported separately for each vowel type. * and $^{tr.}$ refer to $p < 0.05$ and $p < 0.08$, respectively, showing level of significance for main effects and interactions; < or > refers to $p < 0.05$ in the post-hoc test.

Table 3. Summary of Accent effects on V1-to-V2 vocalic kinematics in the vertical (y) dimension

Kinematic measures	/i/-to-/a/ (downward)	/a/-to-/i/ (upward)
Displacement	main effect of Accent: F(1, 5) = 1.65$^{n.s.}$ Accent × V2 Type interaction: F(1, 5) = 9.83* post-hoc: ACC > UNA	post-hoc: n.s.
Peak Velocity	main effect of Accent: F(1, 5) = 2.42$^{n.s.}$ Accent × V2 Type interaction: F(1, 5) = 12.27* post-hoc: n.s.	post-hoc: ACC < UNA
Total Movement Duration	main effect of Accent: F(1, 5) = 2.43$^{n.s.}$ Accent × V2 Type interaction: F(1, 5) = 12.71* post-hoc: ACC > UNA	post-hoc: n.s.
Time-to-peak velocity (Acceleration Duration)	main effect of Accent: F(1, 5) = 5.03$^{tr.}$ Accent × V2 Type interaction: F(1, 5) = 6.91* post-hoc: ACC > UNA	post-hoc: n.s.
Deceleration Duration	main effect of Accent: F(1, 5) = 1.13$^{n.s.}$ Accent × V2 Type interaction: F(1, 5) = 0.56 n.s. post-hoc: n.s.	post-hoc: n.s.

Three-way RM ANOVAs showed no interactions between Accent and Boundary, indicating that Boundary effects are independent of Accent effects, but they showed Accent × V2 Type interactions in some cases. Therefore the results are reported separately for each vowel type. * and $^{tr.}$ refer to $p < 0.05$ and $p < 0.08$, respectively, showing level of significance for main effects and interactions; < or > refers to $p < 0.05$ in the post-hoc test.

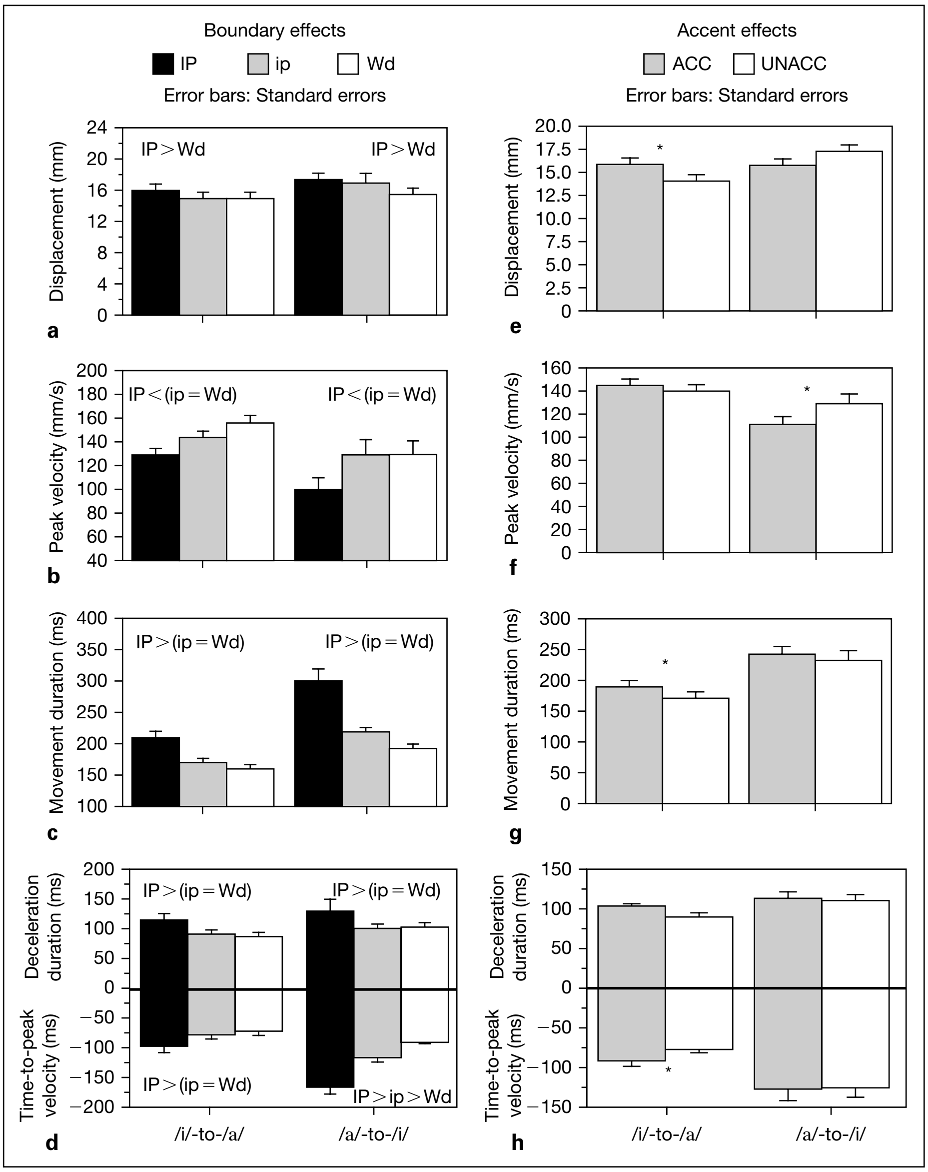

Fig. 2. Effects of Boundary and Accent on V-to-V kinematics (displacement, peak velocity, total movement duration, time-to-peak velocity, and deceleration duration) in the vertical (y) dimension. > and * refer to $p < 0.05$ obtained with post-hoc tests.

3.2. Effects of Accent on the Tongue Kinematics

In the previous section, the Boundary factor showed main effects on all the kinematic measures, with no interaction with V2 Type in most cases. In contrast, the Accent factor revealed no significant main effect on any kinematic measure but it showed its significant interaction with V2 Type for all five kinematic measures. This suggests that the accent-induced kinematic pattern differs consistently depending on whether the vocalic target is /a/ (/i/-to-/a/) versus /i/ (/a/-to-/i/).

Displacement. There was a significant Accent × V2 Type interaction [$F(1, 5) = 9.83$, $p < 0.05$], showing that the accent effect on displacement varied with V2 Type (/i/ vs. /a/). As shown in figure 2e, the interaction stemmed from the fact that only the /a/ target (/i/-to-/a/) was associated with an accent-induced larger displacement, while /i/ target showed no such increase in displacement.

Peak Velocity. The significant Accent × V2 Type interaction [$F(1, 5) = 12.27$, $p < 0.05$] arose from a significantly *lower* peak velocity for accented versus unaccented only for /i/ target (/a/-to-/i/) (fig. 2f). This time /a/ target (/i/-to-/a/) did not show an accent-induced change in peak velocity. This suggests that accentuation does not uniformly influence speed of articulatory movement, and that the accented gesture is not associated with an increase in speed of articulatory movement: the only significant finding was the *decrease* in peak velocity associated with /i/ target.

Total Movement Duration. Total Movement Duration also showed a significant Accent × V2 Type interaction [$F(1, 5) = 12.71$, $p < 0.05$], showing a significantly longer movement duration only for /a/ (but not for /i/) when accented (fig. 2g). This again shows an asymmetrical accent effect that varies with V2 Type.

Time-to-Peak Velocity (Acceleration Duration) and Deceleration Duration. There was a trend effect of Accent on Time-to-peak velocity [$F(1, 5) = 5.03$, $p < 0.07$], showing a tendency towards a longer Time-to-peak velocity when the target vowels were accented versus unaccented. But the significant Accent × V2 Type interaction [$F(1, 5) = 6.91$, $p < 0.05$] showed that the accent-induced increase was associated only with /a/ target (/i/-to-/a/), as shown in the lower panel of figure 2h. Deceleration Duration, on the other hand, showed no such interaction for either /a/ or /i/ target. It was therefore Acceleration Duration that characterizes accent-induced lengthening for /a/, while there was no evidence for accent-induced lengthening for /i/ target. This again suggests that the temporal effects of Accent varied with V2 Type with only /a/ target showing accent-induced lengthening.

4. Summary and Discussion

The present study examined how various kinematic measures for V1-to-V2 lingual gestures in English C1V1#C2V2 context are influenced by Boundary and Accent, and whether the accent and boundary effects are conditioned by V2 Type (/a/ vs. /i/).

4.1. Kinematic Variation as a Function of Prosodic Boundary

The results showed that V1-to-V2 tongue lowering (with /a/ target) and raising (with /i/ target) gestures are kinematically characterized by a longer and slower movement at stronger prosodic boundaries, regardless of accent and V2 type, which is generally consistent with the boundary-induced kinematic patterns reported in Byrd [2000]. The boundary effect did not interact with accent, showing its consistency across accent condition.

The consistent lengthening effect with slower movement (reduced peak velocity) at a stronger prosodic boundary may appear to be compatible with the stiffness account – i.e., the less stiff the articulatory gesture, the slower the movement. If stiffness is the only parameter underlying kinematic differences, there should be a change in peak velocity, but not in displacement, and at the same time, the acceleration duration (time-to-peak velocity) is expected to be elongated [Byrd and Saltzman, 1998; Byrd et al., 2000; Byrd, 2000; see also Cho, 2006, for discussion]. The present study, however, showed that both the raising and lowering gestures are accompanied by an expanded displacement, which cannot be accounted for by variation in stiffness alone. These observations do not make it possible to single out any particular dynamical parameter that might be solely responsible for boundary-induced kinematic differences [see also Cho, 2006, for a similar conclusion].

The fact that the transboundary V-to-V movement was associated with an expanded displacement has another theoretical implication. Based on the results of an acoustic durational study, Barnes [2002] suggested that domain-initial lengthening in English is limited to consonantal articulation because vowel duration is used primarily for marking stress in English. This result was further supported by Cho's [2005] acoustic and articulatory study which showed no domain-initial strengthening in the maximum tongue position (extremum) of the vocalic gesture and its corresponding F1 and F2 values for English /a/ and /i/ in CV syllables. In an electropalatographic study on English CVs (/tɛ/, /nɛ/), Cho and Keating [2007] also showed that domain-initial strengthening is not extended to the postconsonantal vocalic articulation. In contrast, Cho [2006] reported that as far as the lip opening gesture is concerned, domain-initial articulatory strengthening is indeed extended to the postconsonantal vocalic articulation. Based on extreme velum positions, Vaissière [1988] also characterized both initial and prominent segments as '[+strong]'. Fougeron [2001] commented that initial strengthening is comparable to that observed in accented position. The current findings present an additional piece of evidence that lends support to the view that domain-initial strengthening may extend into the lingual gesture beyond the domain-initial consonant. (See also Farnetani and Vayra [1996], who showed more vocalic opening in initial position in Italian CV syllables.) What emerges from the mixed evidence for domain-initial strengthening for the vocalic articulation is that domain-initial strengthening is not entirely absent but likely to be attenuated in the following vowel, still embracing the postconsonantal vowel within the scope of influence of domain-initial strengthening, which can be characterized as a *gradation* effect rather than as an all-or-none constraint.

The gradient locality of the boundary-induced effect can be explained by Byrd and Saltzman [2003] in the framework of a mass-spring gestural model [Byrd, 2000]. As introduced at the beginning of the paper, they hypothesize that articulation at prosodic junctures is governed by the abstract and non-tract variable 'π-gesture' (the prosodic boundary gesture). In this theory, only the constriction gestures, consonantal or vocalic, that are within that temporal field are assumed to be affected, and its strength waxes and wanes smoothly over the temporal field. That is, the π-gesture influences articulation in a gradient fashion, such that the articulations that are close to the prosodic boundary are assumed to be most influenced by the π-gesture, thus inducing the strongest lengthening effect and the effect dwindles as the articulation gets farther away from the juncture. This may explain why postconsonantal vocalic articulation (V in CV) often fails to show boundary effects (not necessarily because it is external to the temporal field of π-gesture, but presumably because its influence on gestures within the field may not be strong enough to give rise to discernible articulatory effects), while domain-initial consonants and preboundary vocalic gestures always show boundary effects.

The theory of the π-gesture, however, does not yet appear to provide a full-fledged account of postboundary (domain-initial) articulation. In what follows, based on the results of the present study, some theoretical concerns will be discussed that are needed to be taken into account in order to further develop the theory of the π-gesture. It should be noted, however, that the following discussion is just to point out what aspects of the theory need to be improved. It is hoped that the advocates of the theory can devise any detailed mechanisms that are necessary to accommodate the data of the present study.

First, the exact scope of the π-gesture's influence in the temporal dimension is not yet clear. In an earlier study, Byrd [2000] suggested that the lengthening of the transboundary V1-to-V2 movement duration at prosodic junctures was due primarily to preboundary lengthening. Byrd [2000] claimed it to be a consequence of a stronger effect of the π-gesture on the preboundary V1: that is, in a C1V1#C2V2 sequence V1 is closer to the prosodic boundary than V2 is, so that V1 is more heavily influenced by the π-gesture than V2 is. However, the results in the present study showed that boundary-induced durational variation is evident quite equally in both the preboundary and the postboundary lengthening, as reflected in lengthening effects on both the acceleration and the deceleration duration of the transboundary V1-to-V2 movement. This is in fact compatible with the results of a later study by Byrd et al. [2006] and Krivokapić [2007], which specifically investigated the temporal scope of the prosodic boundary effects by examining the tongue tip opening and closing movement for coronal consonants. They showed that temporal effects on both preboundary and postboundary articulation are by and large equivalent, especially when it comes to articulation immediately adjacent to the prosodic boundary, although compensatory shortening was observed for the second and the third syllables. The theory of the π-gesture then needs more sophisticated mechanisms to specify systematically how far the effects of the π-gesture can be extended around prosodic junctures and exactly how the scope is determined.

Second, the present study showed that both the accent and boundary factors induced lengthening without interactions between them. This leads to another concern. When an accented gesture occurs at a stronger prosodic boundary, thus being subject to both accent- and boundary-induced lengthening, how much of the lengthening is attributable to the π-gesture's influence which is hypothesized to govern only the boundary-induced articulation and how much is due to the accentuation effect? Saltzman et al. [2007] demonstrated a possible use of π-gesture in accounting for a lexical stress effect on articulatory timing. This opens up a possibility that the π-gesture may be modified to control the articulatory timing for accented gestures as well. Whatever mechanism it might use, the theory needs to devise a way to tease apart the two different lengthening effects.

Finally, a relatively limited body of experimental work that supported the π-gesture hypothesis has characterized the nature of articulation at prosodic boundaries primarily in temporal dimension, as the central clock, which controls the rate of articulatory activation of constriction gestures, is slowed down [Byrd, 2000; Byrd and Saltzman, 2003; Byrd et al., 2006]. Byrd and Saltzman [2003] indeed showed that domain-initial spatial expansion of consonantal articulation [e.g., Fougeron, 2001; Cho and Keating, 2001; Keating et al., 2003] can be simulated by a clock-slowing implementation of the π-gesture as this can reduce the articulatory overlap between domain-initial consonantal gesture and the following vocalic gesture, hence detruncating the consonantal gesture allowing it to reach a more extreme articulatory posture. The present study showed that V2 vocalic gesture in transboundary V1-to-V2 movement is associated with spatial expansion in the vertical dimension. What the theory needs to consider further is then how the influence of the π-gesture captures the boundary-induced lengthening effect which is sometimes accompanied by spatial expansion as found in the present study and sometimes not [e.g., Edwards et al., 1991; see also Byrd, 2006, and Cho, 2006, for relevant discussions].

4.2. Kinematic Variation as a Function of Accent

The results regarding the V2 Accent effect on kinematic variables showed an interesting asymmetry between /i/-to-/a/ and /a/-to-/i/ lingual gestures, differing primarily in peak velocity and displacement. Accentuation of /a/ expressed in the vertical (y) dimension showed a larger, longer, but not faster, downward movement (/i/-to-a/) while accentuation of /i/ showed no such robust effects. The asymmetrical kinematic pattern between /a/ and /i/ suggests that accent does not uniformly influence articulations across vowel type. With respect to accent-induced articulation, de Jong [1995] suggested that accented segments are hyperarticulated in a way to increase articulatory activities, which enhances phonological contrast and therefore lexical distinction [de Jong, 2004]. The present study suggests that the phonological contrast maximization assumed by the accent-induced hyperarticulation is not achieved in an across-the-board fashion, but rather it should be better understood when effects of various factors such as the vowel type (and therefore its relevant articulatory gestures involved) are all taken into consideration. (See Cho [2005] and Tabain and Perrier [2005] for a relevant discussion.)

The present findings also have some implications for the theory of a mass-spring gestural model on speech production. As introduced at the outset of the paper, some previous researchers [Edwards et al., 1991; Harrington et al., 1995] have suggested that the accent-induced variation in the jaw movement is best characterized by a larger and longer displacement with no substantial change in movement peak velocity, which supports the view that the intergestural timing is the major underlying dynamical mechanism that modulates accentuated speech production. In contrast, some others suggested that dynamic aspects of accent-induced articulation are far more complex than has been assumed. For example, accentuation was found to engender a larger (in magnitude), longer (in duration) and faster (in speed) articulatory movement, as found in the lip opening and closing movement [Cho, 2006] and the jaw lowering movement [Fowler, 1995], which cannot be described adequately in terms of a single dynamical parameter setting (e.g., intergestural timing). In the present study, it was found that only the /i/-to-/a/ tongue lowering gesture was associated with an increase in displacement, which was accompanied by increased total movement duration and time-to-peak velocity, but not by a change in peak velocity and deceleration duration – i.e., the movement for accented V2 /a/ is larger and longer, but not necessarily faster. This pattern again does not support any dynamical parameter setting as a single underlying mechanism. For example, the stiffness account is rejected because of lack of variation in peak velocity (stiffness change is expected to induce variation in peak velocity); and the intergestural timing account is rejected because of variation in time-to-peak velocity (acceleration duration; acceleration duration is not expected to vary with change in the intergestural timing). Moreover, what makes it even harder to capture accent-induced articulatory variation in dynamical terms is that the present study introduced two new factors, the vowel type and the kind of articulator that is involved – i.e., prosodically conditioned articulation not only varies with the vowel type (/a/ vs. /i/) with /i/ target showing no robust accent-induced kinematic variation, but it also differs according to articulators (the tongue versus the jaw and the lips). Theories of speech production previously advanced in the framework of a mass-spring gestural model must therefore incorporate effects of these factors into their dynamical parameter-based accounts.

5. Conclusion

The present study investigated effects of two prosodic factors, boundary and phrasal accent, on the transboundary V1-to-V2 lingual articulation in C1V1#C2V2 context in English. The results of the present study lead to a number of conclusions about prosodic influences on V1-to-V2 lingual articulation. They suggest that prosodic strengthening is not expressed uniformly in all articulatory dimensions, but it varies depending on the vowel type. Moreover, the present study has implications and challenges for theories of speech production regarding the dynamical account of prosodic strengthening and the π-gesture model. It implies that not a single dynamical parameter setting can successfully account for kinematic characteristics of prosodic strengthening and that the π-gesture needs to be further refined in order to take into account asymmetrical patterns when different types of vowel and articulators are involved. The fact that the two sources of prosodic strengthening, boundary and accentuation, are characterized by different kinematic patterns suggests that the speakers do differentiate the two sources of prosodic strengthening, supporting the view that speakers must know about different aspects of prosodic structure, prominence and boundary, and take into account both aspects of prosodic structure in phonetic encoding [Keating and Shattuck-Hufnagel, 2002]. All in all, the present study illuminates the interplay between phonetics and prosody, which needs to be fully understood in order to better understand the complex nature of speech production.

Acknowledgments

I would like to thank the 6 subjects for participating in the experiment. Special thanks go to Pat Keating, Sun-Ah Jun, Dani Byrd, Klaus Kohler and a reviewer for their constructive comments and advice on this study. The articulatory data presented here were collected as part of the author's 2001 UCLA PhD dissertation project.

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